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Outline

What Caused GW150914?

Source: Binary Black Hole Merger

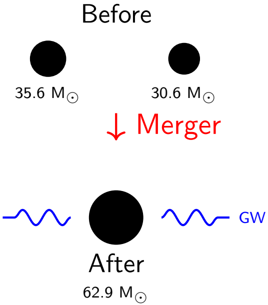
Component Masses

- Primary BH: **35.6 $M_\odot$**
- Secondary BH: **30.6 $M_\odot$**
- Final BH: **62.9 $M_\odot$**

Energy Radiated

$$\Delta M = 35.6 + 30.6 - 62.9 = \mathbf{3.3\,M_\odot}$$

$$E = \Delta M c^2 \approx 5.4 \times 10^{47}\ \mathrm{J}$$



Key Point: 3.3 $M_\odot$ converted to gravitational waves in <1 second!
Peak luminosity: 3.6×10^{49} W (brighter than all stars in the observable universe!)

When and Where?

Event Details

- **Date:** September 14, 2015
- **Time:** 09:50:45 UTC
- **GPS Time:** 1126259462.4
- **Distance:** ∼410 Mpc (∼1.3 billion light-years)
- **Redshift:** $z \sim 0.09$

Detectors

- **LIGO Hanford (H1)** - Washington
- **LIGO Livingston (L1)** - Louisiana
- Baseline: 3,002 km apart
- **H1-L1 time difference:** 7.3 ms

Physics Insight

Why two detectors?

- Confirm real signal (not local noise)
- Sky localization from timing
- Verify signal consistency

Time delay tells us:

- Signal direction
- Came from Southern Hemisphere
- Light travel time H1→L1: ∼10 ms
- Measured: 7.3 ms ✓

Signal Duration and Characteristics

Duration

- **Inspiral phase:** $\sim$0.2 s
- **Merger + ringdown:** $\sim$0.05 s
- **Total visible signal:** $\sim$0.25 s

Signal Properties

Property	Value
Peak strain	$\sim 10^{-21}$
Frequency range	35–250 Hz
Duration	$\sim$0.2 s
Peak luminosity	3.6×10^{49} W

Physics Intuition

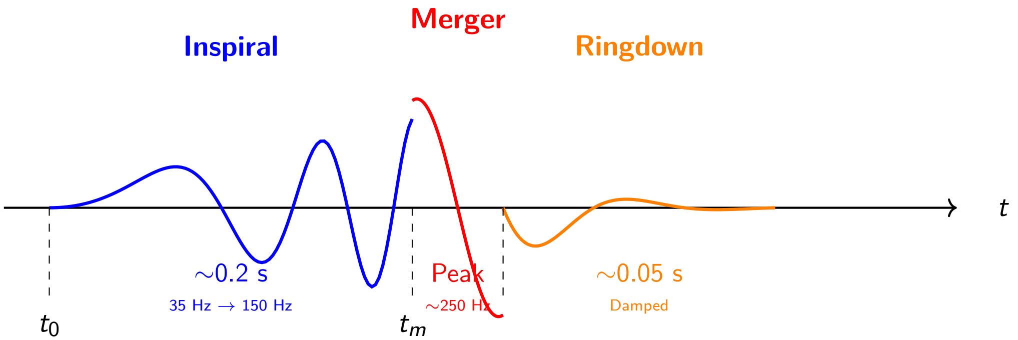
Why so brief?

- BHs orbited for millions of years
- Only last few orbits in LIGO band
- Final plunge is rapid ($<$1 second)

Why this frequency range?

- $f \propto v^3/M$ (orbital frequency)
- As $r\downarrow$, $v\uparrow$, $f\uparrow$ (chirp!)
- LIGO sensitive: 10–1000 Hz
- GW150914: 35–250 Hz ✓

The Three Phases of Merger



1. Inspiral

Physics:

- BHs orbit, lose energy
- $r\downarrow$, $v\uparrow$
- $f\uparrow$, amplitude $\uparrow$
- Chirp signal

2. Merger

Physics:

- BHs coalesce
- Peak strain
- Max frequency
- Highly nonlinear

3. Ringdown

Physics:

- New BH "rings"
- Quasi-normal modes
- Exponential decay
- Tests GR!

Historical Significance

Scientific Milestones

1. **First direct detection** of gravitational waves
2. Confirmed Einstein's 1916 prediction
3. Opened gravitational-wave astronomy
4. Proved existence of stellar-mass binary BHs
5. Nobel Prize 2017

Detection Confidence

- Combined SNR: **24**
- Significance: $>\mathbf{5.1}\sigma$
- False alarm rate: <1 per 203000 years

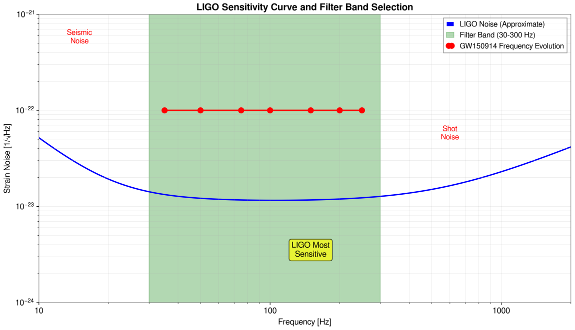
What Made It Possible?

- 50+ years of detector development
- Advanced LIGO $10\times$ more sensitive
- Multi-detector network
- Sophisticated data analysis

Impact

- New window on the universe
- Probe extreme gravity
- Study BH populations
- Test GR
- Multi-messenger astronomy

LIGO Sensitivity and Filter Design



Physics Intuition

Noise sources:

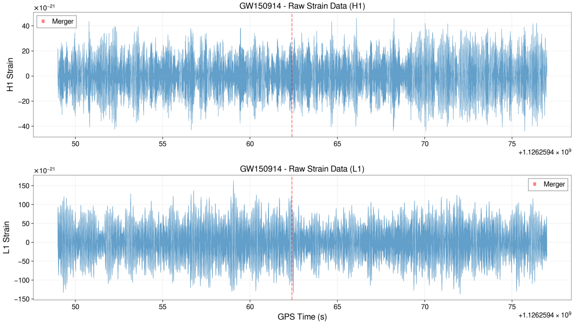
- **Low freq (<30 Hz):** Seismic, suspension thermal
- **Sweet spot (30–300 Hz):** Best sensitivity
- **High freq (>500 Hz):** Shot noise

Filter Choice

Why 30–300 Hz?

- GW150914 chirps through this band
- Maximizes signal-to-noise ratio
- Removes seismic and shot noise
- Captures inspiral + merger

Raw Strain Data



What We See

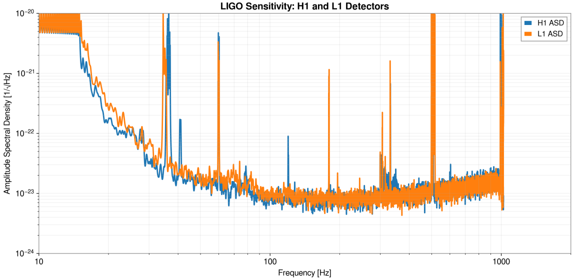
- Signal buried in noise
- Strain $\sim 10^{-21}$
- H1 and L1 both noisy
- Need filtering to see signal

Physics Challenge

How small is 10^{-21}?

- LIGO arm length: 4 km
- Change: 4×10^{-18} m
- $=1/1000$ of proton diameter
- Like measuring distance to nearest star to width of human hair

Power Spectral Density



What is PSD?

Power Spectral Density shows noise power vs frequency

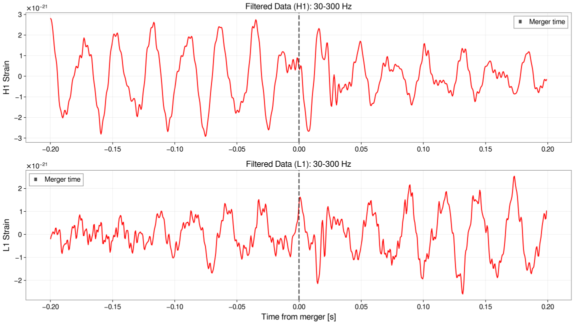
$$S_n(f) = \text{Noise power at frequency } f$$

Lower is better

Physics Insight

- **10 Hz:** Seismic dominated
- **50–200 Hz:** Most sensitive
- **>500 Hz:** Shot noise rises
- H1 and L1 similar sensitivity

Filtered Data: The Chirp Emerges



Band-pass Filter: 30–300 Hz

What happened?

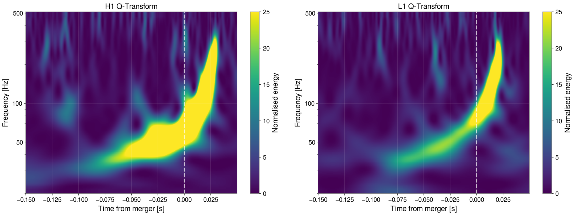
- Removed low-frequency seismic noise
- Removed high-frequency shot noise
- **Signal now visible**

The Chirp Signal

Key observations:

- Amplitude increases with time
- Frequency increases
- Duration: $\sim$0.2 seconds
- H1 and L1 show same pattern
- Time offset $\sim$7 ms

Q-Transform: Time-Frequency Evolution



What is Q-Transform?

Shows frequency content vs time

- Time on x-axis
- Frequency on y-axis
- Color encodes energy

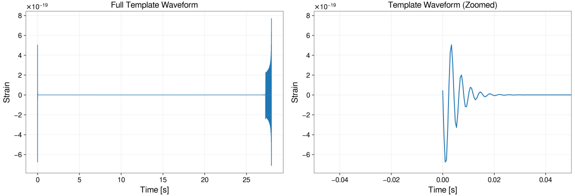
Physics: The Chirp

What we see:

- Track rises with time
- Starts around 35 Hz at t = -0.15 s
- Ends near 250 Hz at t = 0 s
- Brightness increases

Why? $f \propto r^{-3/2}$

Template Waveform Generation



What is a Template?

Theoretical prediction of GW signal

Inputs:

- Mass 1: 35.6 $M_\odot$
- Mass 2: 30.6 $M_\odot$
- Spins (if known)
- Distance, orientation

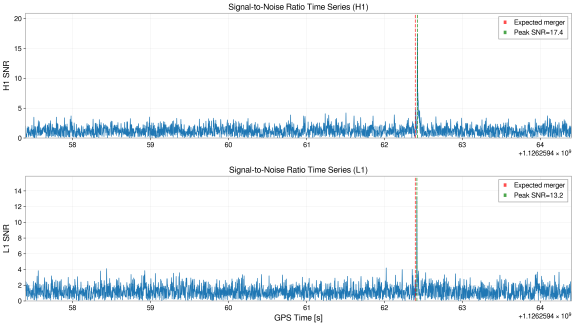
Method: Solve Einstein's equations

Approximant: SEOBNRv4 (Effective One Body)

Physics

Template shows **expected** waveform.
Compare to data $\rightarrow$ find match!

Matched Filtering: Finding the Signal



What is SNR?

Signal-to-Noise Ratio
Measures correlation between data and template:

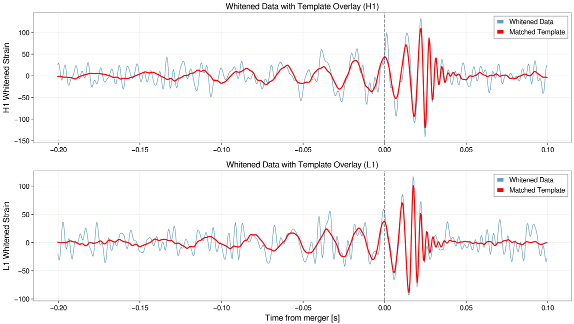
$$\rho = \frac{\langle \text{data} | \text{template} \rangle}{\sqrt{\langle \text{template} | \text{template} \rangle}}$$

High SNR = Good match!

Results

- **H1 peak SNR:** 17.4
- **L1 peak SNR:** 13.2
- **Combined:** ∼24
- Detection threshold: ∼8
- **Clear detection!**

Whitened Data with Template Overlay



What is Whitening?

Normalize noise across frequencies

$$\tilde{h}_{\text{white}}(f) = \frac{\tilde{h}(f)}{\sqrt{S_n(f)}}$$

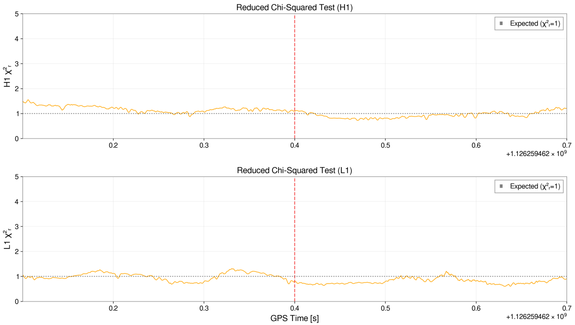
Makes signal easier to see visually

Excellent Match!

Blue: Actual data
Red: Template prediction
Physics: Data follows template almost perfectly!

- Confirms binary BH merger
- Validates General Relativity
- Measures masses accurately

Chi-Squared Test



What is χ^2 Test?

Checks if signal matches template across all frequencies

Divide frequency band into bins, check consistency:

$$\chi^2_r = \frac{1}{N} \sum_i \frac{(\text{data}_i - \text{template}_i)^2}{\sigma_i^2}$$

Expected: $\chi^2_r \approx 1$ for real signal

Glitch: $\chi^2_r \gg 1$

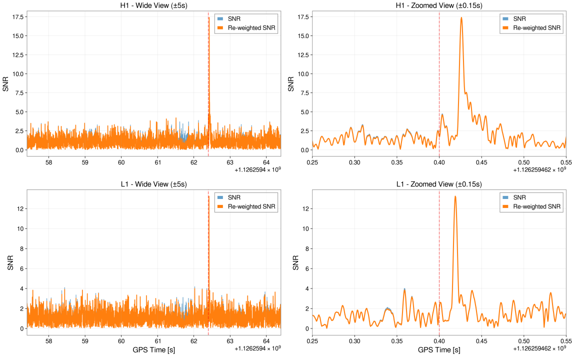
Result

At merger time: $\chi^2_r \approx 1$

$\Rightarrow$ Signal is **consistent** with template!

$\Rightarrow$ **Not a glitch**

Re-weighted SNR



Why Re-weight?

Problem: Glitches can have high SNR

Solution: Penalize high χ^2:

$$\hat{\rho} = \begin{cases} \rho & \chi_r^2 \leq 1 \\ \rho \times f(\chi_r^2) & \chi_r^2 > 1 \end{cases}$$

where $f(\chi_r^2) < 1$ (penalty)

Physics Insight

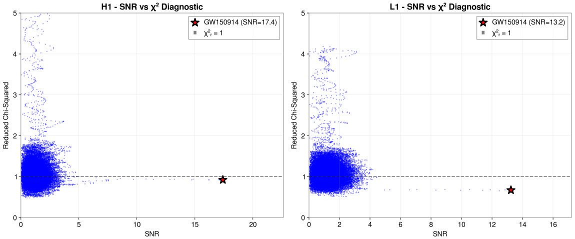
Blue: Raw SNR

Orange: Re-weighted SNR

GW150914 peak: **Not penalized!**

$\Rightarrow$ Real signal, not glitch

SNR vs Chi-Squared Diagnostic



Scatter Plot Interpretation

Each point: One time sample
Blue cloud: Noise
Red star: GW150914

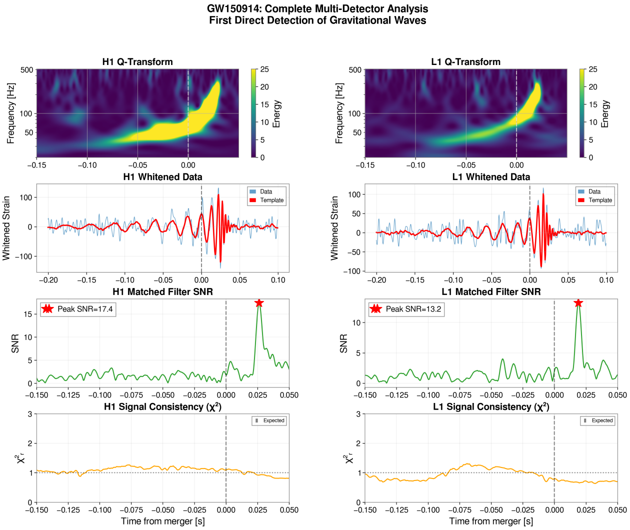
Key Observation

GW150914 properties:

- **High SNR** (17.4 for H1)
- **Low** χ_r^2 (≈ 1)
- Far from noise cloud

Glitches: High SNR and high χ_r^2
Conclusion: GW150914 is a **real astrophysical signal**!

Publication-Quality Figure



Publication Figure: Interpretation

Row 1: Q-Transform

Shows: Time-frequency chirp

- Both detectors see same track
- 35 Hz $\rightarrow$ 250 Hz
- Duration $\sim$0.2 s

Row 2: Whitened Data

Shows: Signal vs template

- Excellent agreement
- Template (red) matches data (blue)
- Validates binary BH model

Row 3: SNR Time Series

Shows: Detection strength

- Clear peaks at merger
- H1: SNR $= 17.4$
- L1: SNR $= 13.2$
- Well above threshold (8)

Row 4: Chi-Squared

Shows: Signal consistency

- $\chi^2_r \approx 1$ at peak
- Confirms not a glitch
- Real astrophysical signal

Key Results Summary

Source Parameters

- **Primary mass:** 35.6 $M_\odot$
- **Secondary mass:** 30.6 $M_\odot$
- **Final mass:** 62.9 $M_\odot$
- **Energy radiated:** 3.3 $M_\odot c^2$
- **Distance:** 410 Mpc

Detection Statistics

- **H1 SNR:** 17.4
- **L1 SNR:** 13.2
- **Combined SNR:** 24
- **Significance:** $> 5.1\sigma$
- **False alarm rate:** $<$ 1/203,000 years

Signal Characteristics

- **Frequency:** 35–250 Hz
- **Duration:** $\sim$0.2 s
- **Peak strain:** $\sim 10^{-21}$
- **Time delay:** 7.3 ms (H1–L1)

Validation Tests

- χ^2 test: PASSED ($\chi^2_r \approx 1$)
- Template match: EXCELLENT
- Multi-detector: CONSISTENT
- Re-weighted SNR: NOT PENALIZED

Physics Insights Gained

What GW150914 Taught Us

1. **Gravitational waves exist** – Einstein was right!
2. **Binary black holes exist** – stellar-mass BH binaries are real
3. **Black holes merge** – we observed the full inspiral-merger-ringdown
4. **General Relativity works** – even in extreme gravity (strong-field regime)
5. **Massive energy release** – 3 solar masses converted to GW in <1 second

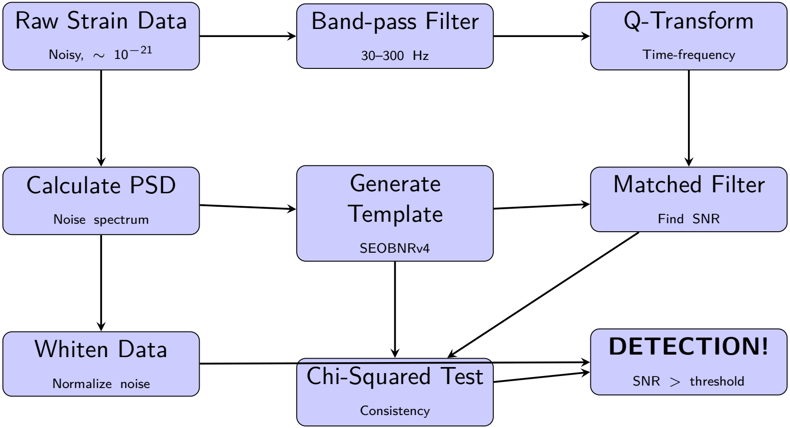
Tests of GR

- Speed of gravity = speed of light
- Waveform matches predictions
- Ringdown frequency matches Kerr BH
- No dipole radiation

Astrophysical Implications

- BH formation mechanisms
- Binary evolution channels
- Merger rates in universe
- Population studies

The Analysis Pipeline in Summary



Multi-stage verification: Each step validates the signal through independent methods

Why Multiple Tests Matter

The Challenge

Problem: Detector glitches can mimic signals

Solutions needed:

- Multiple detectors
- Multiple analysis techniques
- Consistency checks
- Veto transients

GW150914 Passes All Tests

- Seen in both H1 and L1
- Consistent timing (7.3 ms)
- Matches template waveform
- Low χ^2 (not a glitch)
- Passes environmental vetoes

Physics Reasoning

Real signal:

- Arrives at both sites
- Time delay $=$ light travel time
- Frequency evolves smoothly
- Matches GR prediction
- Consistent across frequency bins

Glitch:

- Usually local (one detector)
- Wrong timing if coincident
- Weird frequency content
- High χ^2 (inconsistent)

Beyond GW150914

What Came After

More detections:

- GW151226 (Boxing Day event)
- GW170104, GW170608, GW170814...
- GW170817 (Neutron star merger!)
- $>$90 events in GWTC-3 catalog

Network growth:

- LIGO (H1, L1)
- Virgo (Italy)
- KAGRA (Japan)
- LIGO India (planned)

New Science

- Black hole population studies
- Tests of General Relativity
- Cosmology (Hubble constant)
- Nuclear physics (NS equation of state)
- Multi-messenger astronomy

Future Detectors

- Einstein Telescope (Europe)
- Cosmic Explorer (USA)
- LISA (space-based)
- Better sensitivity
- More sources

Conclusions

GW150914: A Historic Discovery

September 14, 2015

- First direct detection of gravitational waves
- Confirmed Einstein's century-old prediction
- Opened a new window on the universe
- Proved binary black holes exist and merge
- Validated General Relativity in extreme gravity

The Dawn of Gravitational-Wave Astronomy

"We have detected gravitational waves. We did it!"

– David Reitze, LIGO Executive Director

Nobel Prize in Physics 2017

Rainer Weiss, Barry Barish, Kip Thorne

Thank You!

Questions?

References:

- B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 116, 061102 (2016)
- LIGO Open Science Center: `https://www.gw-openscience.org`
- PyCBC Documentation: `https://pycbc.org`